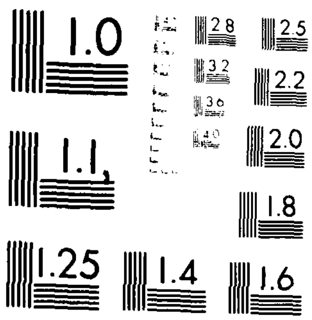
AD-A131 927 AIRCRAFT TRANSPARENCY TESTING METHODOLOGY AND EVALUATION CRITERIA PART 1..(U) DAYTON UNIV OH RESEARCH INST K I CLAYTON ET AL. APR 83 UDR-TR-83-25-PT-1 1/1

UNCLASSIFIED AFWAL-TR-83-3045-PT-1 F33615-81-C-3421 F/G 1/3 NL

END
DATE FILMED
9-83
DTIC



MICROCOPY RESOLUTION TEST CHART

AFWAL-TR-83-3045
Part I

AIRCRAFT TRANSPARENCY TESTING METHODOLOGY AND EVALUATION CRITERIA

Part I - Test Methods and Information Analysis

Kenneth I. Clayton
Blaine S. West

University of Dayton Research Institute
300 College Park Avenue
Dayton, Ohio 45469

April 1983

Final Technical Report for Period January 1982 - February 1983

FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Malcolm E Kelley

MALCOLM E. KELLEY
Project Engineer

R. Harley Walker

R. HARLEY WALKER
Group Leader
Subsystems Development Group

FOR THE COMMANDER

SOLOMON R. METRES
Director
Vehicle Equipment Division

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/FIER, W-PAFB, OH 45433 to help us maintain a current mailing list".

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-83-3045, Part I	2. GOVT ACCESSION NO. AD-A131 927	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AIRCRAFT TRANSPARENCY TESTING METHODOLOGY AND EVALUATION CRITERIA Part I - Test Methods and Information Analysis		5. TYPE OF REPORT & PERIOD COVERED Final Report Jan. 1982 - Feb. 1983
		6. PERFORMING ORG. REPORT NUMBER UDR_TR-83-25
7. AUTHOR(s) Kenneth I. Clayton Blaine S. West		8. CONTRACT OR GRANT NUMBER(s) F33615-81-C-3421
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Dayton Research Institute 300 College Park Avenue Dayton, Ohio 45469		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 24020338
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE April 1983
		13. NUMBER OF PAGES 61
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aircraft transparency testing
Transparency durability
Accelerated weathering
In-service environment
Exposure simulation
Acrylic
Polycarbonate
Laminated Construction

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This two-part report defines a methodology and criteria for testing and evaluating the durability of high performance aircraft transparencies through the use of simulated in-service environments. Part I presents and analyzes relevant information/data on applicable operational environments, candidate test methods, and previously used simulation/testing techniques. Appropriate corrective action is recommended to circumvent

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Continuation of Block 20.

knowledge voids and/or test method deficiencies. A realistic and cost-effective durability evaluation criteria is presented in Part II for monolithic stretched acrylic, coated monolithic polycarbonate, and acrylic faced/polycarbonate laminate configurations.

FOREWORD

The efforts reported herein were performed by the Aerospace Mechanics Division of the University of Dayton Research Institute (UDRI), Dayton, Ohio, under Air Force Contract F33615-81-C-3421. The program was sponsored by the Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. Air Force administration direction and technical support was provided by Mr. Malcolm E. Kelley, AFWAL/FIER, the Air Force Project Engineer, and Mr. R. Harley Walker, AFWAL/FIER.

The work described herein was conducted during the period 18 January 1982 through 18 February 1983. University of Dayton project supervision was provided by Mr. Dale H. Whitford, Supervisor, Aerospace Mechanics Division, and Mr. Blaine S. West, Head, Applied Mechanics Group. Technical effort was accomplished under Messrs. B. S. West and K. I. Clayton as Principal Investigators.

The authors wish to express their appreciation to the ASTM F7.08 committee members, especially those associated with the military aircraft transparency suppliers, for providing helpful contributions and comments relative to the effort reported herein.

TABLE OF CONTENTS

PRECEDING PAGE BLANK-NOT FILMED

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1

INTRODUCTION

1.1 BACKGROUND

The U. S. Air Force recognizes that high performance aircraft transparencies are a high cost item. To date, it has been extremely difficult to predict the durability of a new transparency design when subjected to the operational environment. Deficiencies exist in the present state of the art for (a) simulating environmental conditioning with laboratory test methods, and (b) translating test results into accurate durability predictions.

This program, as part of the USAF continuing effort to improve the cost-of-ownership of aircraft transparencies, is directed to the definition of a realistic and cost-effective transparency test and evaluation criteria. Preliminary steps toward achieving this goal were accomplished during 1981 by AFWAL/FIER as documented in Reference 1 and by UDRI as documented in Reference 2.

1.2 PROGRAM OBJECTIVE

The objective of this effort is to define a methodology and criteria for testing and evaluating the durability of high performance (Fighter) aircraft transparencies through the use of simulated in-service environments. Specific transparency material configurations under study are monolithic stretched acrylic, coated monolithic polycarbonate, and acrylic faced/ polycarbonate laminates.

SECTION 2

INFORMATION ANALYSIS

2.1 ANALYSIS/CORRELATION OF EXPOSURE/TESTING TECHNIQUES

The University of Dayton Research Institute, under contract with the U. S. Air Force, has conducted several programs to evaluate the effects of environmental conditioning on the optical and structural properties of various monolithic coated polycarbonate and laminated acrylic-polycarbonate transparencies. The following discussion correlates the data resulting from these in-house, Government, and industry programs and generates recommendations and conclusions relating to the various exposure conditions and test methods as input for formulating future test criteria. Table 1 presents the number of test samples versus conditions and test methods which have been utilized at UDRI. A brief description of the exposure/test and a comment relating to its usefulness as supported by experimental data is summarized below.

2.1.1 Test Methods

(a) MTS Beam Test (Impact)

The MTS beam test is an instrumented flexure test utilizing three-point simply-supported loading per ASTM D790-71 Method I. The MTS test machine is a high performance electrohydraulic, servo-actuated closed loop general purpose mechanical loading apparatus with high level control and data

TABLE 1

UDRI GENERATED TEST DATA

	F-16 MATERIAL								F-111 MATERIAL - ACTUAL WINDSHIELD						GENERIC POLYCARBONATE						
	Flat Stock						Actual Canopy Material Laminated		ADBIRT		BIRT				Coated		Uncoated				
	Monolithic			Laminated																	
	Texstar P	Sierracin	PPG	Texstar	Sierracin	Goodyear	Texstar	Goodyear	Sierracin Radar Reflective	Sierracin Clear	PPG Clear	PPG Clear	Texstar Uncoated	Texstar P No Test	.125	.31	.125	.25	.31	.5	TOTAL
MTS BEAM	140	40	40	20	20	20							5		10	10	10		10		325
FALLING WEIGHT	158	56	56										7		8	13	9	153	49	21	530
AIR CANNON	27												2						16	15	60
CHEMICAL CRAZE	24	48	48																		120
RAIN EROSION	40	30	31																		101
BAYER ABRADER	20	40	40																		100
FLATWISE TENSION				20	20	20	10	10	27	19	18	15									149
TORSIONAL SHEAR				20	20	20	10	10	17	13	20	17									147
WEDGE PEEL									32	20	20	20									92
SALT ABRADER														18							18
SUNLIGHTER	55	24	24	15	15	15								35							183
QUV	50	24	24											6							104
DSET - EMMA	47																				47
- EMMAQUA	47																				47
NATURAL AGING AT VARIOUS LOCATIONS					460 (in progress)																460
MOISTURE	20																21		28		69
THERMAL	30			15	15	15								11							86
TEMP/HUMIDITY	14	24	24	15	15	15			29	27	29	29		33							2[illegible]4
LAB AGE CONTROL	20																				20
IZOD																	15		15		30
CHARPY																	15		15		30
BASELINE	92	24	24	15	87	15								10							267
																				TOTAL	3,239

gathering capabilities. A mounting fixture is used to provide three-point, simply-supported loading to the center of a specimen; the contact radius of each loading support being 3/8 inch. A span-to-specimen thickness ratio of 8:1 is generally used. Coated monolithic specimens are placed in the fixture so as to produce tension in the coated or exposed test surface under investigation. Laminated specimens are impacted so as to produce tension on the interior surface. The displacement rate is controlled at 2000 inches/minute and is constant during the test; maximum displacement being set at 2.50 inches. The calibrated output signals of both the LVDT (Linear Variable Differential Transformer) and load cell are captured in a dual channel digital transient waveform recorder and later played back on an x-y recorder to document load versus displacement.

The UDRI has performed over 300 MTS beam tests on monolithic and laminated F-16 transparency materials (Reference 3). This test data is repeatable and quantitative, which enables a breakdown of the test data into sections of elastic deformation and plastic deformation or fracture propagation and a determination of attendant mechanical property values. The relative cost of the apparatus is high. The basic result of an MTS beam test is a force versus displacement plot from which the yield strength and energy to failure (for a specific beam configuration) can be determined. The energy to failure (area under the force versus displacement curve) and the shape of the curve can be compared for a material after various exposure conditions to determine if embrittlement occurred. Figure 1 superimposes the load-displacement curves for a material in the baseline condition and after exposure; notice the exposed EMMAQUA specimens fail prior to the baseline unexposed material, which indicates the material was embrittled by the exposure.

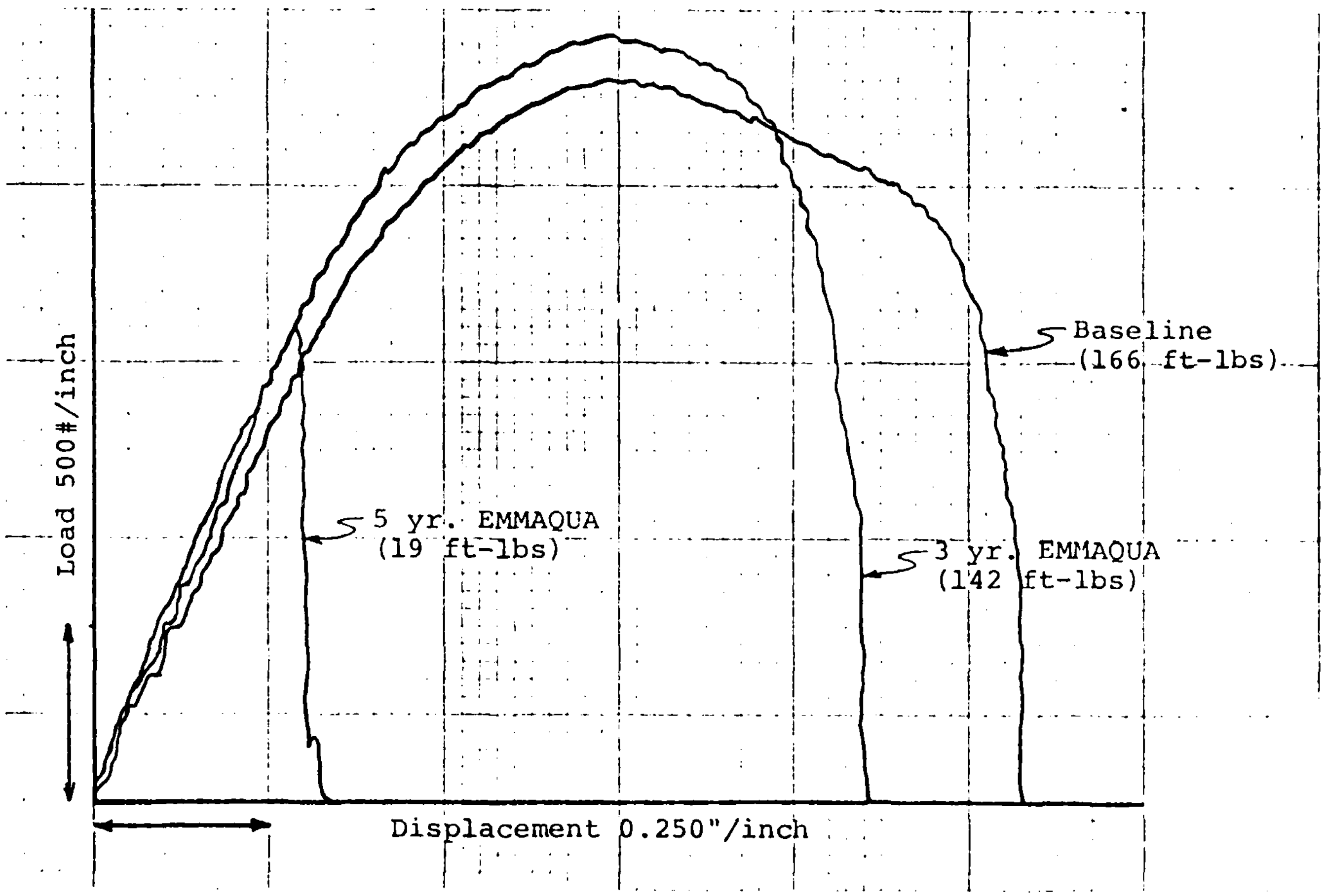


Figure 1. Typical Load vs. Displacement Plots; MTS Beam (2000 in/min).

(b) Falling Weight Impact Test

The falling weight impact tests, conducted in accordance with ASTM F736-81, utilize either three-point, simply-supported flexural beam loading or a ring support, clamped or simply-supported, for flat plate loading (Reference 4). Impact velocities of approximately 25 to 34 ft/sec, corresponding to drop heights of 10 and 18 feet, have been achieved. The tester, which was designed, fabricated, and installed at the University of Dayton, will accommodate simply-supported or clamped plate specimens of various span/thickness ratios as well as simply-supported beams of varying span/thickness ratios. A lifting carrier is provided to raise or lower the impactor to a maximum drop height of 20 feet, adjustable and measurable to the nearest half-inch. Drop weights are detachable, interchangeable, and variable in known increments from one pound to a total of 50 pounds. Hemispherical impactors from one-quarter-, one-half-, one-, one and one-half-, and two-inch diameter geometry are available and interchangeable for impact testing of plates. A 2.25-inch-wide impactor loading nose and adjustable supports, corresponding to ASTM D790-71 Method I, are available for three-point impact testing of simply-supported beams. A two-cable system guides the falling weight so that it will repeatedly strike within 0.10-inch of center of the specimen at an impact velocity approaching free fall. Automatic release and rebound catch mechanisms are provided along with a protective enclosure used to contain any flying particles which may be generated during test. A miniature accelerometer can be mounted in the impactor housing to obtain a load-time history when desired. The signal from the accelerometer is triggered two inches before impact by a photocell, and received throughout the impact event. The accelerometer signal is integrated twice to obtain velocity and displacement, a scaling factor being used to

obtain force. An x-y recorder is utilized to play back, at reduced speed, the test data which has been stored in the memory of a transient recorder. The goal of this testing is to produce threshold of failure in the specimen; threshold of failure being defined as a visible open crack. The mass and height are iterated during testing to determine the energy level required to achieve threshold of failure. The threshold of failure energy for a material is calculated from the height and mass of the falling weight impact which results in a visible open crack. This energy level can be compared for a material after various exposure conditioning to determine if embrittlement has occurred.

The falling weight test is a useful and economical test method for determining embrittlement or softening of a material. Table 2 shows results of tests conducted on coated monolithic F-16 polycarbonate which had been environmentally conditioned. Note that the conditioning had dramatic effects on the failure threshold energy.

(c) Notched Izod Impact

The standardized notched Izod test method (ASTM D256-73, Method A) yields qualitative results, but requires a test sample with a critical machining operation (notching). Attempts have been made to quantify this test method but as yet an instrumented specimen has not been generated. The specimen is clamped in a vertical position in a bise using fixturing to precisely locate the notch in reference to the test frame. The striking nose of the pendulum then strikes the sample at an initial velocity of 11.4 ft/sec at a point 0.866 inches above the notch. The side of the specimen with the notch faces the impactor. One result of notching is an effective increase in the strain rate in the material; hence the geometry of the notch and

TABLE 2

FALLING WEIGHT IMPACT TEST RESULTS

Specimen Number	Exposure Condition	Failure Energy, ft-lbs.	Failure Type*
143	Baseline	150	D
277		175	P
199		150	D
145		175	F
208		175	F
210		175	F
144		175	F
177	UV-3 yr.	200	D
224		225	D
196		225	D
183		250	F
204		250	F
156		250	F
230		265	F
147	UV-10 yr.	325	D
146		350	F
221		350	F
120		325	F
141		350	F
96	EMMAQUA-2 yr.	150	P
8		150	P
27		125	P
82		150	P
107		100	P
46		75	P
78	EMMAQUA -3 yr.	175	P
114		150	P
99		150	P
105		125	P
112		125	P
7		75	P

* D = Ductile
F = Failure
P = Penetration

the method of fabrication must be carefully controlled to insure the validity of the test. The energy expended in deforming or fracturing the specimen is calculated by deducting the values for the residual energy in the pendulum and losses due to friction and windage in the apparatus from the initial energy to the pendulum. In the case of sheet material, the direction of loading is in the plane of the material and perpendicular to the direction of rolling unless the direction of loading is a variable in the test matrix. In comparison with the air cannon and falling weight methods, the size of the specimen for the notched Izod method is much smaller and the cost of the apparatus is typically less, but since transparency materials are notch sensitive, use of this test technique is not recommended (Reference 5).

(d) Notched Charpy Impact

The notched Charpy test method (ASTM D256-73 Method B) is very similar to the notched Izod method. The Charpy test specimen is loaded in simply supported three-point flexure as opposed to the fixed cantilever beam loading employed in the Izod test method. Both tests use the same test machine, utilizing different supports and impactor heads. In the notched Charpy test, the impactor loading nose strikes the specimen directly behind the notch, and the support span is 3.75 inches. In both tests, the impactor velocity decays as the specimen is deformed or fractured, the amount of decay being dependent upon the energy of the impactor and the rate of energy absorption in the specimen. As with the Izod test, its application to notch sensitive transparency materials is not recommended.

(e) Air Cannon Tests

Air cannon tests are used to evaluate the high strain rate characteristics of a transparency material. Coupon size plate specimens are used to evaluate material impact resistance and are usually tested with either a one-inch-diameter steel sphere or a one-inch-diameter, 3-inch long hemispherically ended cylinder shot from a 1-1/2-inch bore, six foot long cannon. Full scale transparencies are also tested using various size artificial birds shot from air cannons. The projectiles are accelerated with compressed air or, for higher velocities, a powder charge that can be used to attain velocities of over 3000 ft/sec. Table 3 presents the results of air cannon tests conducted on coupon size specimens of F-16 coated material; this material being very sensitive to coating embrittlement. The air cannon test method is a most useful test method, but has the highest cost per test especially if a significant amount of instrumentation is used. The test results are usually qualitative in nature and relatively large amounts of material are required. The primary advantage is the high impact strain rates which are attainable, providing realistic bird impact testing of a subscale and/or full-scale structure.

(f) Flatwise Tension

Flatwise tension tests of laminated materials have been conducted using ASTM Method D952 as a guide. The test is designed to determine the interlaminar flatwise tensile stress required to delaminate the material. Specimens have ranged in size from one to two inches square, and have been successfully fabricated from flat and curved transparency material. The specimens are bonded to aluminum fixturing blocks and tested in an electrohydraulic MTS tension machine. Force versus

TABLE 3

AIR CANNON TEST RESULTS

Specimen Number	Exposure Condition	Velocity Ft/Sec	Failure (1)	Comment (2)
346	Baseline	555	D	GR212
353		622	D	GR212
358		655	F	GR212
365		623	F	GR212
370		602	F	GR212
351		195	F	
354		142	D	
361		175	D	
367		196	F	
371		188	D	
UN-13		917	D	Uncoated
UN-14		1024	F	Uncoated
369	EMMA-1 yr.	146	F	
373		134	D	
374		140	D	
375		151	D	
376		172	D	
377	EMMAQUA-1 yr.	172	F	
378		164	D	
379		182	D	
380		196	D	
381		229	F	
348	UV-1 yr.	188	F	
352		178	F	
357		164	D	
364		193	D	
372		215	D	

[1] F denotes specimen failure exceeding threshold

D denotes ductile deformation below failure threshold

[2] Coating C-254-1C tested opposite impact unless otherwise noted

displacement data is recorded and plotted. This is a useful test for determining the interlaminar flatwise tensile strength, stiffness, and toughness of a laminated material. Figure 2 shows a comparison between test results of two different urethane interlayers and a silicone interlayer.

(g) Torsional Shear

Torsional shear tests of laminated material have been conducted on both flat and curved material using ASTM Method E229 as a guideline. The test is designed to determine the interlaminar shear strength and shear modulus of a material without inducing bending, peeling, or transverse shear. Torque is applied to the specimen through a clamping fixture with an electrohydraulic MTS tension-torsion machine to produce a peripherally uniform strain distribution through the test annulous. The nonlinear (non-Hookian) interlayer materials result in a nonlinear stress distribution which may result in the calculation of an erroneous shear strength as described in Figure 3. Test results are also sensitive to shear strain rates as shown in Figure 4. Table 4 shows the results of tests conducted on the same laminated transparency material using specimens differing only in geometry. The disk specimens demonstrated a high "apparent" shear strength, approximately 50% greater than the annular specimen, due to the effects of geometry[6,7].

The torsional shear test is considered a useful test method for analyzing the interlaminar shear properties by minimizing the possible nonlinear effects. It is useful to analyze the shear strength of an interlayer since the relationship between tensile and shear properties of an interlayer is not always known. Table 5 summarizes the results

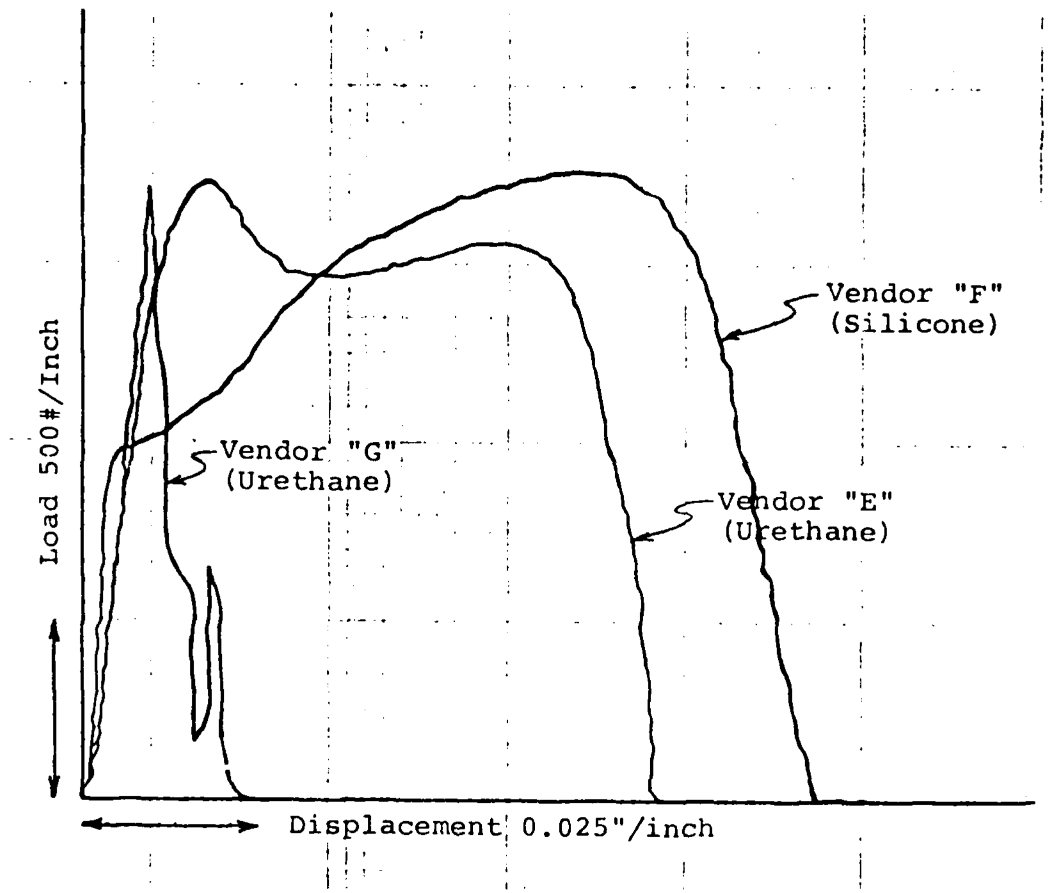


Figure 2. Typical Load vs. Displacement Plots; Flatwise Tension.

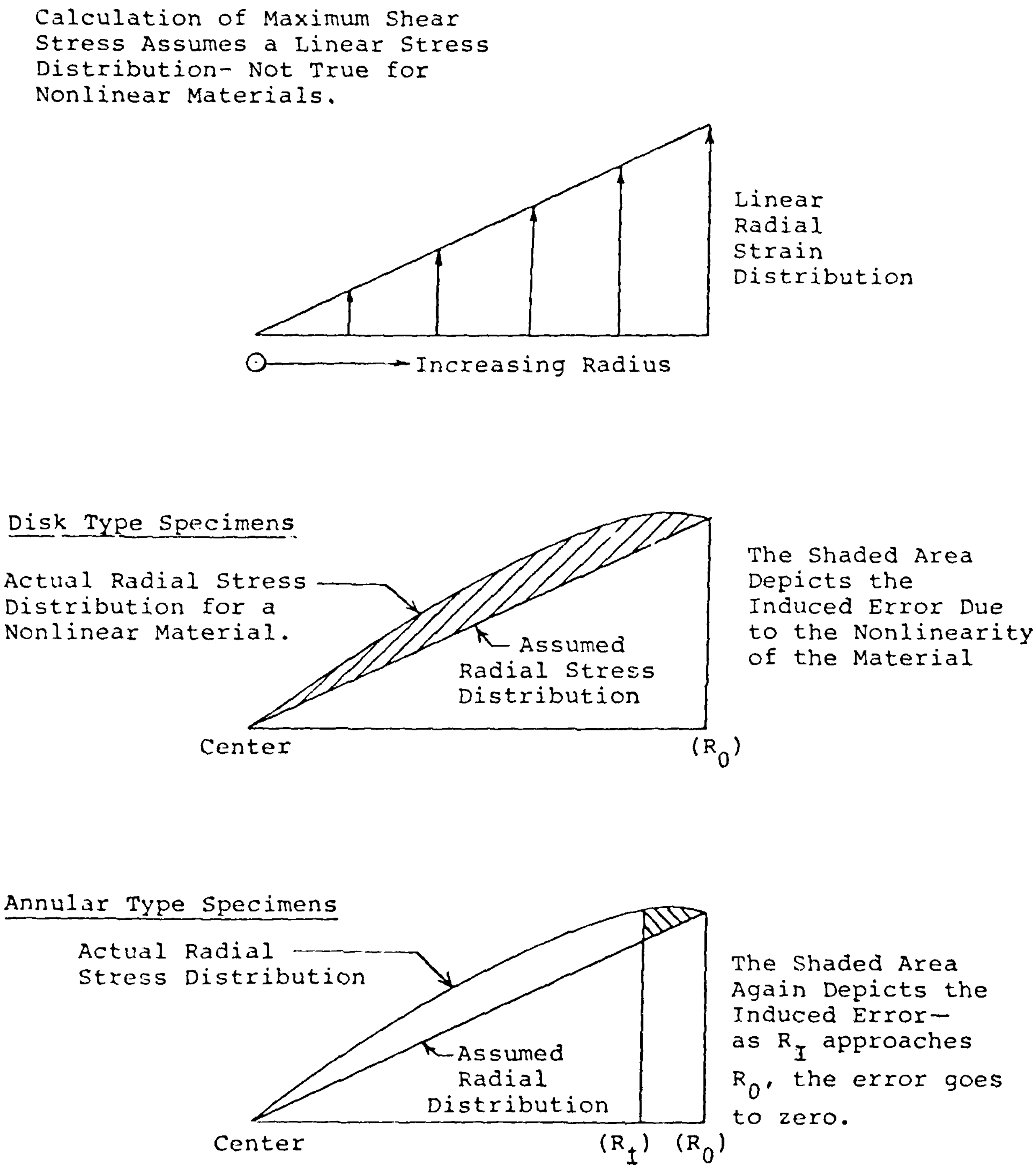


Figure 3. Summary of the Effects of Nonlinear Material Properties on the Results of Torsional Shear Tests.

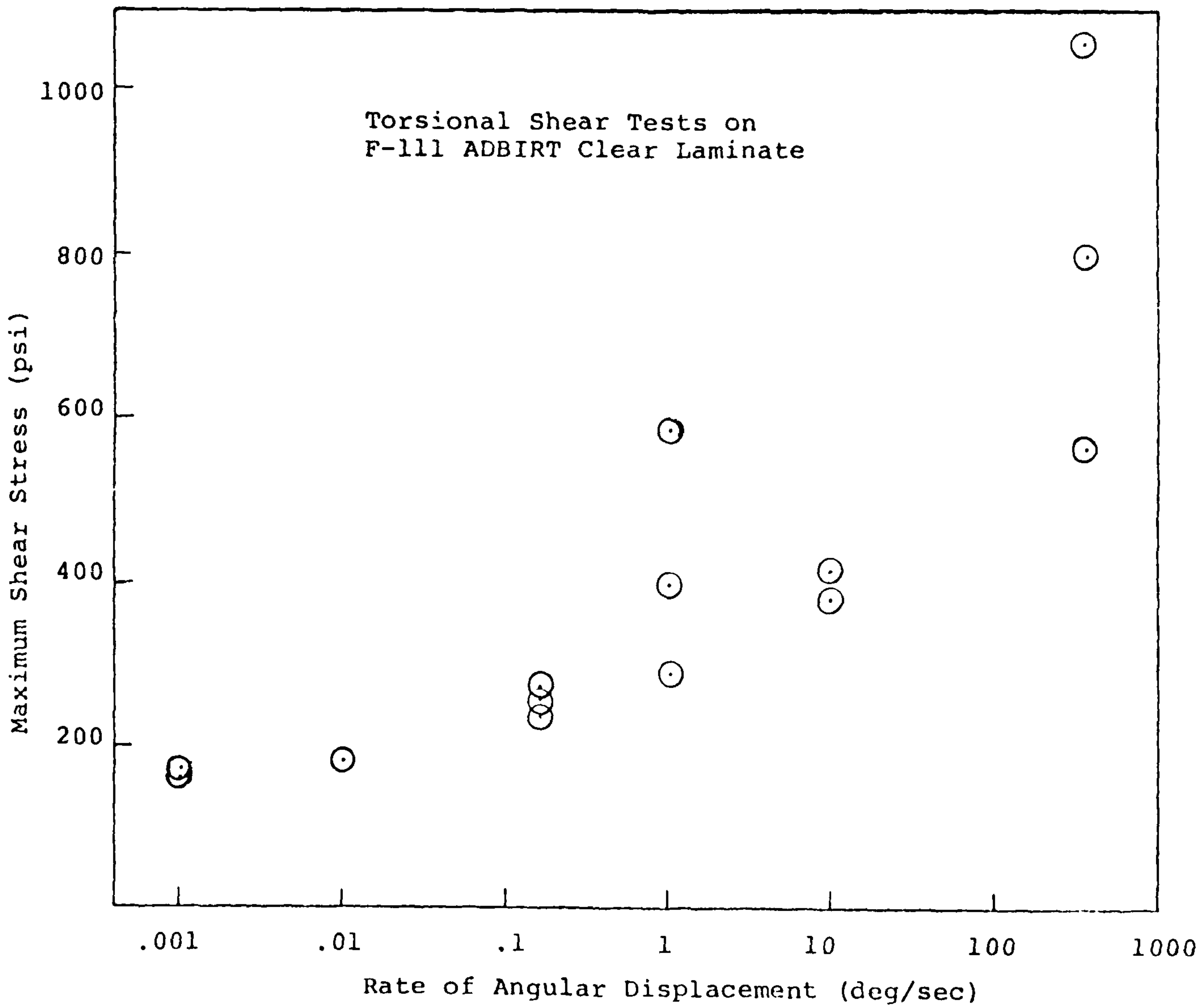


Figure 4. Effects of Test Rate on Shear Strength.

TABLE 4

TORSIONAL SHEAR TEST RESULTS
FOR F-16 CANOPY MATERIALS

Test Specimen Size: Annular Type $r_0 = .375 \pm .002$
$r_i = .250 \pm .002$

Disk Type $r_0 = .375 \pm .002$

Test Rate = 500°/sec (2.73 in/sec Average Linear Rate)

Specimen Identification	Configuration Type	Failure Type	Max Torque (T max) (in/lb)	Angular Disp at T max (Degrees)	Max Shear Stress (PSI)
C-1	Annular	A	148	17.8	2226
C-2	Annular	A	134	16.3	2016
C-3	Annular	A	146	16.0	2196
C-4	Annular	A	136	17.5	2046
C-5	Annular	A	143	17.5	2151
C-6	Disk	A	238	23.8	3580
C-7	Disk	A	219	20.5	3295
C-8	Disk	A	244	24.5	3671
C-9	Disk	A	229	23.3	3445
C-10	Disk	A	233	22.0	3505

Failure Type: A = Adhesion Off Acrylic

$$\text{Max. Shear Stress} = \frac{\text{Torque (Outside Radius)}}{\text{Polar Moment of Inertia}}$$

TABLE 5

FLATWISE TENSION TEST RESULTS (PSI)

Specimen	Exposure Condition	Vendor EV	Average	GV	Average
1	Baseline	2270 A*		2425 P**	
2		2370 A		2675 P	
3		2165 A	2297	2725 P	2720
4		2395 A		2900 A	
5		2285 A		2875 P	

TORSIONAL SHEAR TEST RESULTS (PSI)

Specimen	Exposure Condition	Vendor EU	Average	GU	Average
1	Baseline	1000 A*		2388 A	
2		1109 A		2388 A	
3		1064 A	994	2338 A	2339
4		983 A		2304 A	
5		815 A		2276 A	

* A = Adhesive Failure on Acrylic Surface

** P = Adhesive Failure on Polycarbonate Surface

of flatwise tensile tests and torsional shear tests conducted on two different urethane interlayers. The flatwise tensile strengths were nearly identical; however, the shear strength of the Vendor G material is over 100% greater than the shear strength of the Vendor E material. Note that the failure location of the Vendor G material also changed.

(h) Bayer Abrader Test

The Bayer abrader test has been used to evaluate the ability of a surface to resist scratching and rubbing erosion. Test specimens (4 x 4 inches square) are positioned in a 4 x 4-inch cavity of the test bed so that the specimen surface is flush with the bottom of the test bed. One kilogram of 6/14 quartz silica sand is placed over the specimen. A mechanical linkage to an electric motor moves the test bed in a back and forth motion and 4-inch stroke length at a frequency of 150 cycles per minute (300 strokes per minute). This action causes the silica sand to remain virtually at rest, inducing a rubbing type abrasion on the specimen. Haze measurements are taken initially (unabraded) and after 50, 100, 150, and 300 strokes using a standard sphere Hunter Hazemeter and Gardner Photometric Unit manufactured by Gardner Laboratory, Inc., Bethesda, Maryland. The construction of the hazemeter used is described in ASTM Test Method D1003.

The Bayer abrader test is considered useful for determining the ability of a transparency material to resist surface scratching and can discern differences in abrasion resistance as a result of environmental conditioning. Table 6 presents a sampling of results of tests conducted by UDRI on candidate coated F-16 canopy material. To date, no correlation has been made with in-service data. However, the data in Table 6 indicate that the number of strokes will have to be greatly reduced to obtain haze values in the range of interest.

TABLE 6

ABRASION TEST RESULTS

	Strokes	Percent Haze Vendor A	Vendor B	Vendor P
Baseline	0	2.74	1.56	2.17
	50	8.20	25.23	10.62
	100	16.76	31.83	17.51
	150	19.82	36.23	16.94
	300	29.03	50.19	22.26
2 Yr. Temp/Hum.	0	3.69	3.72	2.70
	50	20.67	30.33	19.81
	100	24.77	42.11	19.03
	150	28.49	48.88	20.88
	300	38.34	63.27	30.46

NOTES: All data above is the average of the five samples per set.

All samples were abraded a total of 150 cycles (300 strokes) per minute, using a four-inch stroke. One kilogram of 6/14 quartz silica sand was discarded after each specimen test.

(i) Salt Abrader

The salt abrader test is designed to evaluate the abrasion resistance of the surface of a material by blasting the surface with small grains of salt. Salt is used because it has approximately the same molar hardness as ice crystals. The amount of abrasion is measured in terms of haze and transmittance. UDRI has conducted a limited number of these tests which appear to be useful in evaluating resistance to inflight surface abrasion.

(j) Rain Erosion Test

To date, rain erosion tests offer one of the most realistic methods of evaluating coating adhesion. Tests have been conducted on coated polycarbonate using the AFWAL Material Laboratory's rotating arm apparatus (Reference 8). Specimens are mounted on a rotating arm which travels through simulated rain at speeds of 500 mph or less, inclined at 30 to the direction of motion. The water droplets are controlled to a 2.0mm diameter and the amount of "rainfall" is also controlled.

This test is useful in determining the inflight abrasion properties of a coating. As the test data presented in Figure 5 shows, differences in coating adhesion is readily apparent; however, there has been no correlation between the results of this test and in-service data.[8]

(k) Chemical Craze Test

Chemical craze tests, based on MIL-P-83310(USAF), Paragraph 4.5.5.2 of Section 4, and FTM 406, Method 6053, are conducted to determine the resistance of a transparency

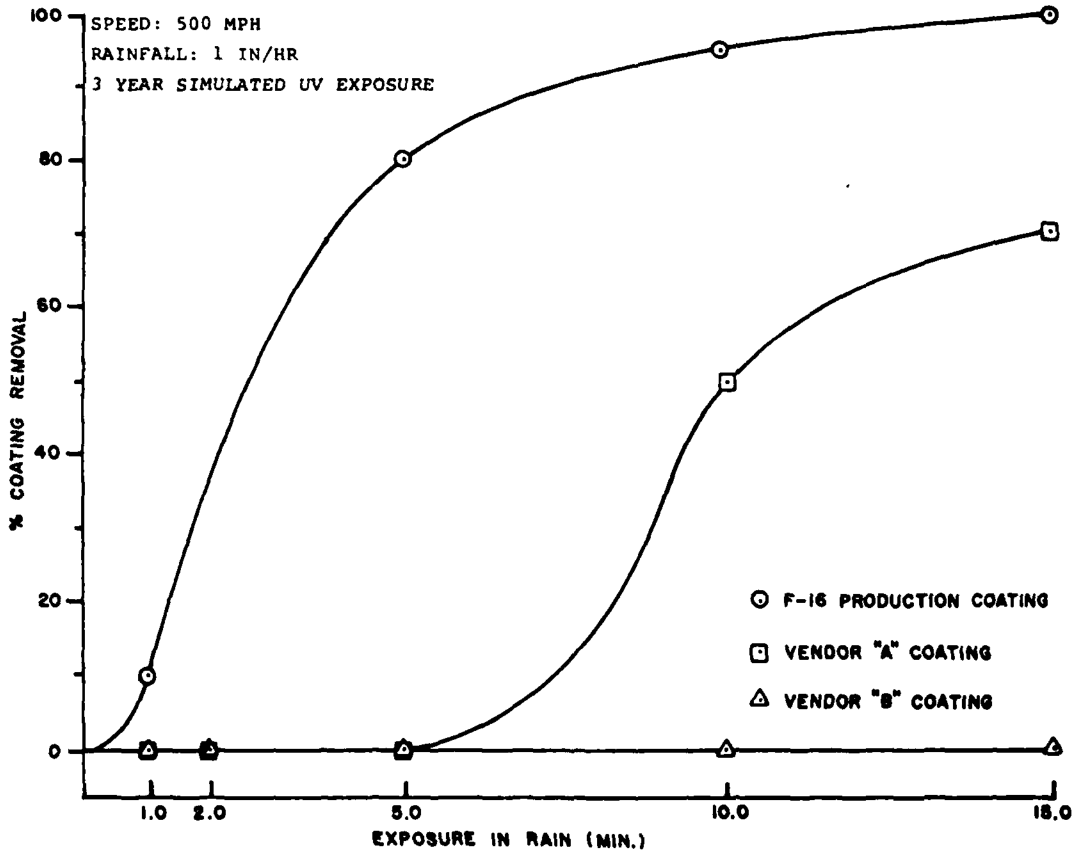


Figure 5. Percent Coating Removal vs. Time in Rain at 500 MPH.

material's surface to chemical crazing. Crazing is defined as microcracking of the surface of a material, and results in an increase in percent haze. The test involves visually determining if crazing occurs in a specimen at a given time (30 minutes) and surface stress (2000 psi) for a given solvent (isopropyl alcohol, ethylene gylcol, and MEK have been used by UDRI). The surface stress is generated by applying a known load to the end of a cantilevered beam test specimen. The solvent is applied to a filter paper which is placed directly on the specimen over the fulcrum. The patch is removed after 30 minutes and the surface visually examined. Table 7 presents typical data from tests conducted on coated monolithic polycarbonate material.

Currently a craze specimen is under development where the solvent is applied along the length of the beam and each specimen generates a stress versus time to craze plot. The chemical craze test is a useful test to perform on coated monolithic material. On laminated acrylic polycarbonate transparencies, the craze resistance of the outer acrylic ply is generally a function of transparency geometry, ply configuration, and flight profiles which determine the surface stress and therefore the service life in terms of crazing.

(1) Wedge Peel Test

Wedge peel tests are used to qualitatively determine the interlaminar peel strength of a laminated material. The primary advantages of this test are that specimens can be exposed to environmental conditioning in the stressed state and the cost of the test is low. The test consists of inserting a wedge into a slot machined into the edge at the end of a beam type specimen. This results in delamination of the material and the length of delamination is measured as a function of time.

TABLE 7

CHEMICAL CRAZE TEST RESULTS

Specimen Number & Vendor	Conditions	Solvent	Failure/ Total Time	Observations
AY-5 AY-6	Baseline	MEK	30 minutes 30 minutes	Coating is deformed and slightly discolored; small crazes (1/32") under patch area
BY-5	Baseline	MEK	48 seconds	Complete failure.
BY-6	Baseline	MEK	30 minutes	Coating is discolored; peeled and cracked.
PY-5 PY-6	Baseline	MEK	30 minutes 30 minutes	No discoloring or deformation of coating; very slight crazing
AY-17	2 Yr. Temp/ Hum. (120°F)	MEK	9':30"	Large craze appeared at 1':40"
AY-18		MEK	30 minutes	Numerous small crazings into polycarbonate; slight discoloration of coating
BY-17	2 Yr. Temp/ Hum. (120°F)	MEK	30 minutes	6':45" crazing appeared; large 3/8" deep crazes formed
BY-18			17':30"	9 min. crazes formed; complete failure
PY-17	2 Yr. Temp/ Hum. (120°F)	MEK	30 minutes	Dissolving & slight discoloring on surface;
PY-18			30 minutes	20 min. small crazing appeared; numerous small crazes, both specimens

Generally, the results of this test (delamination length) are compared qualitatively with materials of similar ply configuration. Quantitative results are not easily obtained because of the difficulty in accurately calculating the stress at the point of delamination. To date, UDRI has limited this test method to testing interlayers that are not faced with a thin surface ply. Figure 6 shows the results of tests conducted on two F-111 ADBIRT transparency specimens; the decrease in the interlayer adhesive strength as a result of moisture being readily apparent.

(m) Zero Tensile Strength Temperature Test

The zero tensile strength temperature test may be utilized as a fast screening or evaluation test for candidate interlayer materials. A sample is lightly loaded and exposed to increasing temperature at a programmed rate. The temperature at which the sample, after elongation, breaks is the zero tensile strength temperature[9].

2.1.2 Environmental Conditions

(a) Sunlight

The Sunlighter IV accelerated sunlight tester, manufactured by the Test-Lab Apparatus Company, Amherst, New Hampshire, consists of four GE RS-4 sunlamp bulbs mounted over a rotating turntable. The tester components, associated power, and control electronics are mounted in a box enclosure with a tinted plexiglas viewing door. One sunlamp bulb is mounted directly over the center portion of the turntable and three additional bulbs are mounted over the outboard portion of the turntable.

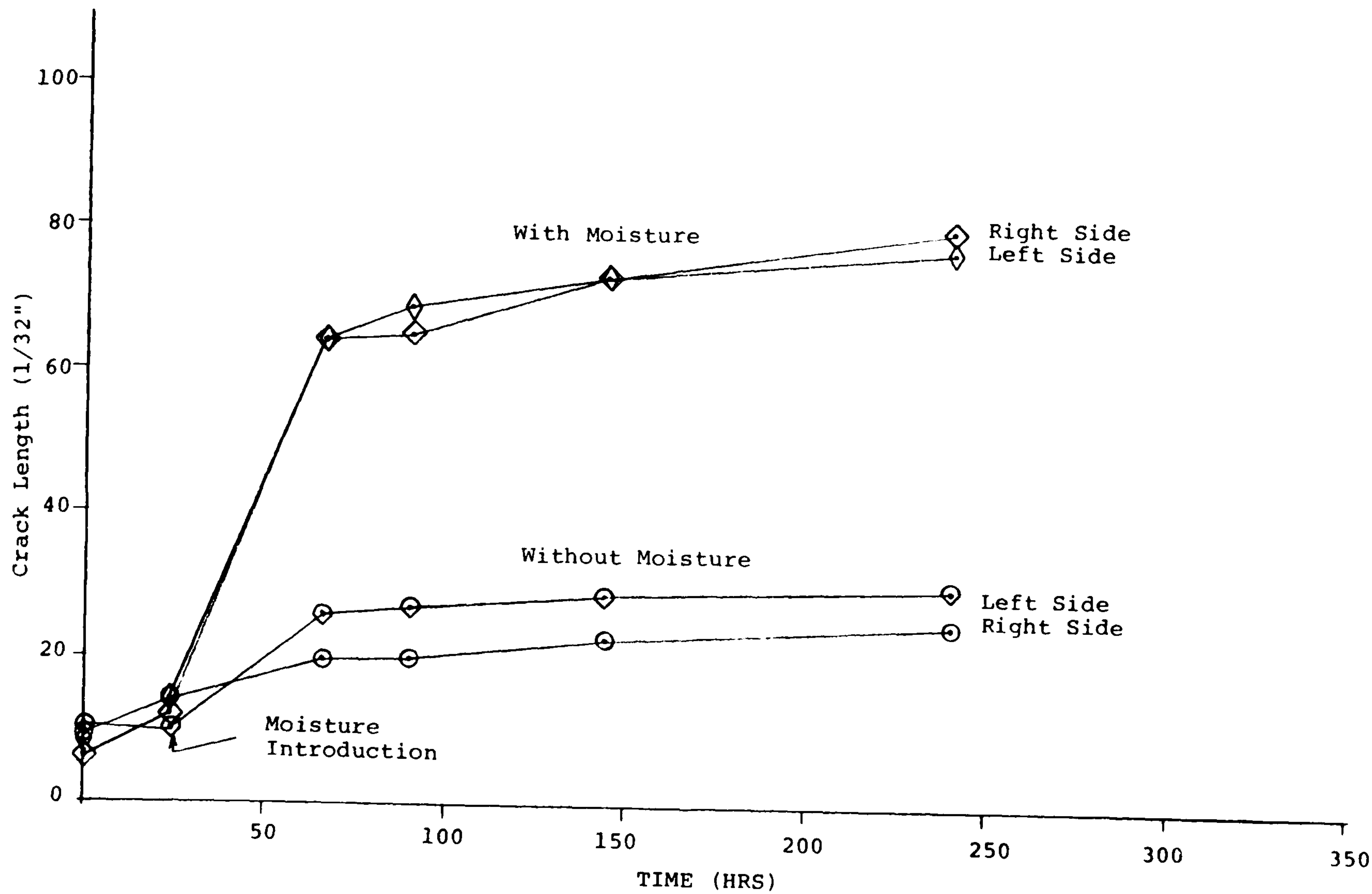


Figure 6. Summary of Wedge Peel Tests.

Consequently, two areas with different exposure accelerations are produced on the turntable, an inner circle of approximately six inch diameter, and the remaining outer ring to 17.5 inch diameter. For the inner circle, the acceleration ratio is approximately eight hours exposure: one year natural sunlight. For the outer ring, the acceleration ratio is 56 hours exposure: one year natural sunlight, according to the manufacturer. The test evaluates the ability of a material to resist degradation due to UV light. There has been no correlation between this exposure condition and in-service data because natural weathering involves many more combined effects than isolated UV. Therefore, this conditioning is not recommended for accelerated weathering type exposure of transparencies.

(b) Temperature and Humidity

Temperature and humidity conditioning has been performed in an environmental conditioning chamber controlled to a temperature of 120 F with simultaneous 95 percent ± 5 percent relative humidity. The test is useful for evaluating the moisture resistance of both laminated and coated materials; however, this should not be considered a test of weatherability. To date, there has been no correlation between these tests and actual in-service life. Table 6, which presents the results of the Bayer abrasion tests, shows a reduction in the abrasion resistance of the coatings due to the temperature/humidity cycle. Placing specimens in a partial vacuum after exposure may be a useful technique for simulating the rapid drying experienced during an aircraft takeoff and acceleration to flight speed.

(c) Combined Conditioning

The F-16 combined conditioning used at UDRI consists of periods of UV exposure alternating with periods of room temperature/high humidity exposure. The procedure is identical to that used for individual exposure conditions. The following sequence has been used to obtain a simulated year of exposure: a period of eight hours in the inner circle of the Sunlighter IV, followed by a period of 48 hours in the room temperature/95 percent relative humidity chamber. Again, this is not considered equivalent to a natural weatherability test. Simultaneous exposures have proved to be more realistic than alternate cycles of individual (isolated) exposure conditions.

(d) Thermal Exposure

Thermal exposures have been conducted at steady-state temperatures of 120°F, 200°F, or 250°F as desired, in an air-circulating oven having a heating and cooling rate of 3-5°F/minute. This is a valid test for evaluating the effects of elevated temperatures on a monolithic or laminated transparency material.

The intermittent exposure of polycarbonate aircraft windshields to temperatures between 176°F and 266°F could cause a cumulative loss in impact properties and the development of stresses from relaxation of any cold-drawn material formed during fabrication. These phenomena will depend on fabrication procedures and the thermal history utilized by the manufacturer (Reference 10).

(e) Natural Weathering

Natural weathering is the most realistic of all exposure techniques; however, the duration of the exposure is prohibitively long. Natural aging of coupon or subscale specimens lack the stresses which would exist in and are imposed on an actual installed full-scale formed transparency during an in-service life cycle spectrum. Since regional weather varies and weather never duplicates itself, it is said that "every outdoor exposure is an artificial weathering test." The mounting of test samples, angle of exposure, and direction of exposure (such as 45^0 South), along with the general procedure to be followed for the exposure of plastics to outdoor weather, is recommended per ANSI/ASTM D1435-75 standard.

(f) Accelerated Outdoor Weathering

Accelerated outdoor weathering of simulated one, two, three, and five year exposure has been accomplished by utilizing the Equatorial Mount with Mirrors for Acceleration (EMMA) and the EMMAQUA machine (EMMA plus water: eight minutes per hour spray cycle) at the Desert Sunshine Exposure Test (DSET) Laboratory located 25 miles north of Phoenix, Arizona. It is estimated that 40 days of exposure on the EMMA and/or EMMAQUA machine is approximately equivalent to one year of 45-degree south natural weathering. The specimens receive about eight times as much radiation as those exposed on a follow-the-sun rack during equal periods of time. Each simulated year was based on an exposure rate of 164,250 langleys. An evaluation of optical, physical, and/or mechanical properties can be conducted after exposure. Both EMMA and EMMAQUA appear to be among the best accelerated weathering techniques currently available, but correlation with in-service experience is still lacking.

An essential requirement of accelerated exposure is that it depend only on the total dose (number of langleys) and not the rate. Materials tested to date on EMMA(QUA) experience an apparent accelerated rate of degradation of from 8 to 12 times when compared with identical specimens tested by conventional outdoor methods. The rate of acceleration depends on the type of material being tested and the season during which the exposure is conducted. Gloss-retention and color-difference of enamels have correlated well. Such correlation factors remain to be determined for transparency material control specimens exposed using EMMA(QUA) and real-time natural weathering.

(g) Q-U-V

The Q-U-V Accelerated Weathering Tester, manufactured by the Q-Panel Company of Cleveland, Ohio, consists of eight 40-watt UV-B fluorescent lamps which operate in a cabinet designed to produce condensation (dew) on the surface of the tested specimen. Exposure temperature is automatically controlled, as is the daily sequence of UV periods and condensation periods. The Q-U-V is one of the better laboratory accelerated exposure systems; simulating sunny days and hot/wet nights. UDRI has tested a limited number of Q-U-V conditioned samples which indicate that this is a useful device for simulating weathering exposure.

Texstar Plastics utilizes a Q-U-V tester to condition specimens to generate coating adhesion data (tape peel test) and evaluate the capability of coated transparency materials to withstand sunlight exposure (haze/transmittance). Extensive testing has been accomplished on GR-212 and C-254 coated polycarbonate samples using 16 hour UV/8 hour high condensation cycles with a constant 120°F heat application.

(h) WPAFB Bldg. 65 Flightline Environmental Exposure Fixture and Convective Heating/Cooling Facility

UDRI has designed and fabricated an accelerated flightline environmental exposure facility which has been incorporated into the full scale F-16 canopy pressure/temperature flight cycle test facility at WPAFB. The flightline environment will be simulated using a specially constructed movable exposure fixture. The effects of UV radiation, solar heating, moisture, and cleaning will be represented.

The convective heating/cooling equipment uses low velocity hot and cold air to duplicate the exterior canopy surface temperatures and change rates that would be experienced during actual flights. The interior canopy air temperature is maintained at 70°F and the pressure differential between the interior and exterior (ambient) also matches the cockpit pressure differential experienced in flight. The system utilizes liquid nitrogen for the cold air source, a large heating system for the hot air source, a network of large diameter pipes for transporting the air, and various blowers and valves to control the velocity and temperature of the air. Dry air is used in the system, a necessity considering the problems that would result from ice formation in cold portions of the system. There are numerous sensors that indicate temperatures and pressures on and inside the test specimen, plus indicators of system performance. Computer and recording systems can "fly" the programmed missions and record the data. Transparencies can be subjected to temperature/pressure profiles corresponding to virtually any aircraft mission, including hypothetical high performance aircraft.

The laminated test canopy will receive a combination of flight (2000 simulated flight hours exposure) and 104 cycles of flightline environment which will simulate 3 years

of worst case UV radiation in a hot and humid environment, plus cleaning. The test canopy will be cleaned using the cleaning solutions and materials authorized for use on installed canopies. The canopy will be subdivided into sections, each section being cleaned with different cleaning solutions or combinations thereof; the cleaning being performed during each changeover from flightline to flight testing.

The test/exposure technique addresses the specific F-16 mission requirement. Full-scale and associate. F-16 flight/flightline test data is currently being generated at this facility which will continue to be monitored and correlated with other associated test results.

(i) WPAFB Building 65 Radiant Heating Fixture

Testing has also been conducted on F-111 transparencies (ADBIRT) to reproduce visible structural deterioration (delamination) by simulating the flightline temperature encountered during the summer months at Cannon AFB. The test fixture consisted of an F-111A crew module and a shroud which contained quartz infra-red heating lamps to control the exterior temperature of the transparencies. An interior cabin heater and blower were added to the module to produce the desired 200°F interior cabin temperature. The heater consisted of twenty, 150-Watt calrod heaters and the blower had a 150 cubic foot per minute capacity at full power. Control of the heater and blower held the interior cabin temperature to within ±10°F of the transparencies outer surface temperature. The flightline environmental test series consisted of subjecting the transparencies to 360 thermal cycles, with each cycle consisting of heating the exterior surface of the transparencies from ambient temperature through 160°, 180°, and 200°F plateaus over an eight-hour period at atmospheric pressure. A proof of load pressure test was added at the conclusion of the 360 thermal cycles. Resulting delamination, prior to design modification

(bushing adhesion), was typical of that occurring in the operational limits at Cannon AFB. However, some test result uncertainties were also experienced which may have been due to absorption of radiant energy by an inner ply or interlayer, thereby creating a temperature gradient through the transparency thickness which would not occur on the production aircraft.

(3) Sierracin Windshield Flight Environment Simulator[11]

Traditionally, the real world of actual service has been the test bed on which windshields have been developed and refined. As windshields become increasingly sophisticated, they become both more expensive and more failure prone, and the economics of service life become more and more significant. The service and laboratory experience gained on the 747 windshield, and its subsequent counterpart, the Lockheed L-1011 windshield, suggested that two of the three aspects of the actual service life environment which play key roles in determining the service life of a windshield are, in fact, almost always missing in conventional accelerated life testing. These essential conditions are (1) weathering, and (2) representative temperatures and temperature gradients within and adjacent to the heated area. The third important factor, pressurization deflection, is usually present in conventional testing.

Results from actual service exposure, confirmed by weatherometer testing in the laboratory, showed that moisture ingress into the interlayer coupled with ultraviolet (UV) radiation, has a significant effect in reducing the laminate integrity. Conventional qualification testing rarely, if ever, acknowledges and imposes these conditions.

Conventional accelerated life testing on windshields usually employs a representative outside air temperature (OAT) but does not duplicate the convective heat loss or

"cooling rate," Q_c, of high speed flight in dry air. This convective heat loss, Q_c, equals the product of the convective film coefficient, h_c, and the temperature differential between the windshield's outer surface and the adjacent boundary layer.

The worst-case flight simulation condition is the one in which high h_c and low boundary layer temperature combine to create the highest Q_c, hence the coldest windshield surface temperature.

Based on this knowledge, a commitment to produce a specialized test facility for accelerated windshield life testing was made by Sierracin. The design requirements for this facility were as follows:

1. Ability to reproduce the convective film coefficient, h_c, of all flight conditions.
2. Duplication of the boundary layer temperature of all flight conditions.
3. Reproduction of the pressurization deflection and resultant stressing of the windshield.
4. Maintenance of cabin-side temperature.
5. Realistic application of windshield power.
6. Duplication of air flow pattern on windshield surface.
7. To the extent possible, reproduction of the fuselage deflections at the windshield interface.
8. Realistic sequencing of all of these conditions into a representative flight profile on a compressed time scale.
9. Inclusion of the effects of moisture, ultraviolet exposure, and rain.

10. Visual and photographic observability of windshields under test.

These conditions were met with a facility called the Sierracin Windshield Flight Environment Simulator (WFES) which has proven the importance of full simulation of the service and flight environment in life testing aircraft windshields. It has been used successfully on an existing design (the 747) to accurately reproduce known service deficiencies, and has provided the means for developing and verifying fixes.

2.1.3 Behavior of Polycarbonate Subjected to Exposure/Testing Techniques[12]

Tensile creep test data at room temperature for polycarbonate is similar to that for stretched acrylic. However, at elevated temperatures polycarbonate offers considerably more resistance to tensile creep.

Degradation of polycarbonate impact strength indicated by Izod test data do not correlate well with results from other tests and might be peculiar to the Izod test. For example, other test methods such as the falling ball, or "dart" impactor, show no such effects. Typical values obtained from this latter method exceed 60 ft-lbs at room temperature and are not affected by temperatures as low as -100°F, nor do thicker samples exhibit brittle fracture as they do in the Izod test.

Like stretched acrylic, polycarbonate has some peculiar temperature-related constraints placed upon it by its basic structure. Polycarbonate's general susceptibility to solvent attack is more pronounced at elevated temperatures and/or when the material is stressed. Use of a protective hardcoat will reduce but may not eliminate this hazard.

Weathering resistance of polycarbonate has not been thoroughly evaluated since it is not possible to duplicate the effects of actual service on an accelerated basis in the laboratory. Additionally, most of the various polycarbonate configurations are so new that not much natural weathering or field service data is available for correlation to the laboratory exposures.

2.1.4 A Review of Microclimatic Weathering Factors[13]

A plastic sample is affected only by its "microclimate"--the conditions at its immediate surface. Among the factors involved in plastics degradation, the most important is the ultraviolet (UV) portion of the sunlight spectrum with wavelengths below 400 nanometers (nm). This varies from 2.8% of the total solar energy in January to 5.0% in August for Phoenix, Arizona (an important test site). Radiation between 290 and 315 nm was three times as intense in September as in January. Total solar radiation, which includes about 53% infrared, is less variable. Samples exposed south at a 45° angle, the usual test condition, received 12,000 langleys in December, compared with 15,600 in April in Miami; respective values for Phoenix are

15,000 and 18,000 langleys. There are indications that the ratio of UV under 400 nm to total sunlight may be about the same throughout the U.S. on any given day. Atmospheric haze can reduce the UV below 400 nm by a factor of 5.

Rain can be highly seasonally dependent. Average annual rainfall also varies greatly by location, ranging from almost zero to well over 100 inches per year.

Air temperature variations with season are well documented, but the temperature of the exposed material determines degradation rates. Solar absorptivity ranges from 0.2 for white surfaces to 0.9 for black, while surface conductance is proportional to wind velocity. For a black material, when the air is 90°F, the sol-air temperature (S.A.T.) is 120°F for a 5 mph breeze and 165°F with no breeze. Note that temperatures of 200°F have been measured for insulated roofing materials, while 170°F black bulb temperature are found on the Nigerian desert. By the rule of thumb that reaction rates double for a 10°C rise, an increase of 45°F (from 120°F to 165°F) would accelerate hydrolysis and secondary photochemical reactions sixfold. The role of air temperature presumably accounts for the greater effect of latitude on degradation than insolation values would suggest. As an example of seasonal variation, weathering conditions in Tennessee are said to be ten times more severe in summer than winter.

Stress is a vital factor and has been utilized in accelerating polyethylene weathering for test purposes. Molded-in stresses have caused rapid failure of cellulose acetate butyrate outdoors. Thus, degradation of unrestrained test samples is liable to be decelerated relative to that under actual stressed conditions if cracking and crazing are the failure criteria.

The actual factors of weather are at work during outdoor exposure, but conditions are nonreproducible due to uncontrollable microclimatic variations. In contrast, accelerated tests provide reproducible conditions. On the average, Weather-Ometers were found to duplicate Florida weather better than Florida weather duplicates itself. Two methods are used in accelerated weathering machines: continuous exposure and intensified exposure. As an example of the former, simulated noon sunshine is maintained in the Xenon-arc Weather-Ometer. This high light intensity persists for at most a few hours a day in nature. As an example of intensified exposure, natural sunlight is concentrated eight times by mirrors in the EMMA device. The appropriateness of these exposures is a disputed subject. It has been suggested that continuous exposure is more reliable than intensified exposure because the latter can cause extraneous reactions. The correlation of Xenon-arc with outdoor data was found to decrease when the radiant energy exceeded a critical level characteristic of individual polymers. Xenon-arc emission bears the closest similarity to solar energy in the UV region, having the highest intensity of energy below 3500A. Wavelengths which cause degradation of polymers (oxidation, chain scisson, crosslinking) are in the near ultraviolet, 3000-4000A. However, acceleration effected through increased intensity alone may fail to give good correlation with natural weathering. Secondary processes promoted by temperature, oxygen, and moisture play a major role in polymer degradation and vary with polymer formulation. For this reason, acceleration of only the primary process by increase in intensity can distort the results even if the spectral distribution is maintained constant.

For some materials, the EMMA test has corresponded well with outdoor exposures in arid climates. With the addition of water-spraying (EMMAQUA), correlations are obtained with wetter climates such as Florida. A simplified Weather-Ometer-like device is the QUV Cyclic Ultraviolet Weathering Tester. This simulates sunny days and hot/wet nights.

Recent years have seen closer duplication of sunlight and better temperature control. In addition, there is more meaningful rain/dew simulation, exposure to aggressive air pollutants such as sulfur trioxide, more sophistication in reporting both weather and plastic test data, and the beginnings of statistical analysis.

Key factors such as UV, temperature, moisture, stress, and thickness of section should be studied separately and in combinations to provide an understanding of degradation mechanisms. Then arbitrary microclimates may be studied in the laboratory and eventually computer-simulated to give degradation curves (or equations). Fitting of early degradation data by a sensitive analytical method such as infrared spectroscopy to these curves would allow long-term predictions with a degree of confidence. The key to long-term prediction lies in a better understanding of the degradation mechanisms rather than in closer simulation of ever-changing weather conditions.

There are several difficulties in quoting and using data from the weathering literature, which has been called "somewhat confused." For instance, commercial formulations have changed over the years. Thus, amber polycarbonate samples become embrittled in three years in Alaska or Panama (1964), whereas later polycarbonate samples showed no significant changes in tensile strength or elongation after three years in Panama or any other sites (1970). Better UV stabilization of the more recent material could explain this. Other difficulties are the

qualitative/subjective nature of much data and incompletely defined formulations and test procedures. In addition, microclimatic conditions are not really known. It is only in recent years that the reporting of regional weather data has become more detailed. For example, instead of sun-hours, the langleys of sunlight (total energy) are now given. However, even this is inadequate because of the component of importance (UV) varies widely with the season, amount of haze, etc. A great deal of weathering data is proprietary and not published at all. Finally, because better UV stabilization is always a possibility, the lifetimes reported must be considered lower limits. Also, it has been postulated that impurities in polymers absorb UV and initiate breakdown. Purer commercial polymers may be developed in the future without these problems.

UV-stabilized polycarbonate material (Lexan 103-112) showed no loss in tensile strength or elongation after three years in hot/dry or hot/wet Australian sites. This result contrasts strikingly with a drop of 80-83% in six months for the unstabilized polymer. Exposures in New Jersey, New Mexico, and Panama gave the same result. This material (Lexan 103-112) after five years in Florida showed no loss in tensile yield strength, 41% loss in elongation, 34% increase in notched Izod impact strength, 62% loss of gloss, 6% loss in light transmission, and a haze increase from 3.6 to 29.9%. This loss in elongation was not considered serious since both Izod and falling ball impact strength increased. Yellowing was slight; the yellowness index increased from 5.0 to 9.7. Another UV-stabilized polycarbonate, Merlon M-50, gave similar results. After three years in Arizona, the elongation fell 31%, the notched Izod impact strength fell 2%, gloss fell 79%, light transmission fell 6%, and haze (a surface effect) increased from 0.5 to 10%.

2.2 CANDIDATE TEST PARAMETERS AND EXISTING STANDARDS

Initially, sixty-one test categories were compiled as being relevant to the mechanical/physical, optical, electrical, and environmental characterization of the transparency materials systems under study. These test categories were formulated into a questionnaire (reference Appendix A) and circulated to recognized authorities and users for input to the program. Confidential responses were received from representatives (ASTM F7.08 members) of Goodyear Aerospace, PPG Industries, Sierracin/Sylmar, Swedlow, and Texstar, enabling the candidate test/exposure categories to be narrowed down to thirty as listed in Table 8. However, categories are included which received such comments as: test not valid--needs humidity and UV; for QC only; for specific designs; takes too long to get results; don't know what results mean; for source comparison only; and published values OK to use. After a final screening by the authors, the thirteen test and four exposure simulation conditions recommended and defined in Part II are those which we consider influential in evaluating the durability of high performance USAF transparencies, namely: surface/chemical craze, haze/transmittance, interlaminar bond integrity (delamination), coating adhesion, coating embrittlement, impact, thermal shock, inflight abrasion resistance, flightline abrasion resistance, edge member attachment, subscale impact, full-scale pressure/temperature/durability, full-scale birdstrike, accelerated weathering, accelerated weathering plus salt blast abrasion, accelerated weathering plus stress, and the Building 65 (W-PAFB) environmental test facility.

Although strength/modulus test methods are not included for the basic in-plane material properties of tension, compression, or shear, it should be noted that only a limited design allowable data base exists when considering the effects of temperature, strain rate, environmental conditioning, etc., on such parameters for either the structural plies or interlaminar materials.

TABLE 8

TEST PARAMETERS FOR EVALUATING THE DURABILITY OF AIRCRAFT TRANSPARENCIES

Transparency Material Configuration:

A. Monolithic Stretched Acrylic
B. Coated Monolithic Polycarbonate
C. Acrylic Faced/Polycarbonate Laminate

Test/Exposure Category		Test Method Recommendation: Per Standard or Preferred	Test Method Recommendation: Alternate	Evaluation/Comments
MECHANICAL/PHYSICAL:				
Bearing Strength	ABC	FTMS 406-1051	ASTM D-953	Published data adequate for sheet stock. For specific design, would opt for subscale lab tests of 3-pt. loaded edge attach beams (high rate MTS).
Bond Integrity (Adhesion)	A	-	-	N/A
	B	QUV plus stress (SEM inspection)	Pain erosion rig plus Acc. weather (SEM inspection)	For coating adhesion; invalidate scribed tape test.
	C	Flatwise Tension (ASTM D952) and Torsional Shear (ASTM F-734 and D-229)	ASTM F-521-77	
Creep	ABC		FTMS 406-1053	Use heat/humidity/time cycles
Fatigue	ABC		FTMS 406-1061	Life cycle for specific design
Impact (Coupon)	ABC	ASTM F-736-81 (fall. wt.) FTMS 406-1074	MTS Beam	
Impact (Subscale)	ABC	Air Cannon		
Impact-Bird (full scale)	ABC	ASTM F-330-79		Customer req'd (AEDC)
Internal Strain (birefringence)	ABC		Polarized Light	Rainbowing limits need defined

TABLE 8 (continued)

Transparency Material Configuration:

A. Monolithic Stretched Acrylic
B. Coated Monolithic Polycarbonate
C. Acrylic Faced/Polycarbonate Laminate

Test/Exposure Category	[illegible]	Test Method Recommendation: Per Standard or Preferred	Test Method Recommendation: Alternate	Evaluation/Comments
Melt Flow Index	A			
	B	ASTM D-1238	ASTM D-1925	Source comparison (QC)
	[illegible]	ASTM D-1238		Monolithic plies
Molecular Weight	[illegible]	[illegible]		Polycarbonate substrate most critical
Peel Strength	[illegible]			N/A
	B			Ref. bond integrity for coating adh.
	[illegible]	[illegible]	90° peel (NASA Brief 65-10173) T-peel (ASTM D-1876)	Vendor spec; need std.
Surface [illegible]	[illegible]	[illegible]	FTMS 406 6053 ASTM F-484-77	Revise to vary solvents & stress; add UV/humidity plus baseline; UDRI evaluating new specimen
	[illegible]	MIL-P-[illegible]	FTMS 406-6053	
	[illegible]	MIL-P-8184B	FTMS 406-6053 (AECMA PrEN2155-19)	
Toughness (Resistance to Crack Propagation K Factor)	ABC	AECMA-PrEN 2155-21	MIL-P-25690A	Monolithic Plies
OPTICAL:				
Angular Deviation	A	MIL-P-25690	ASTM F-733	User requirement for each specific design. (Need std.)
	B	MIL-P-83310	FTMS 406-3041	
	C	Aircraft Critical Item Spec.	Measurement Device	Aerospace Medical Research Lab., WPAFB, OH.

TABLE 8 (continued)

Transparency Material Configuration:

A. Monolithic Stretched Acrylic
B. Coated Monolithic Polycarbonate
C. Acrylic Faced/Polycarbonate Laminate

Test/Exposure Category		Test Method Recommendation		Evaluation/Comments
		Per Standard or Preferred	Alternate	
Flaw Detection	ABC		Visual/optical scan with point light source or edge lighting	Need std.
Haze & Transmittance	A	FTMS 406-3022		Good inspection of optical degradation after exposure
	B	ASTM D-1003		
	C	ASTM D-1003 and FTMS 406-3022		
Scratches	ABC	ASTM F-548	ASTM F-[illegible]8	
ENVIRONMENT:				
Abrasion Resistance	ABC	QUV & stress plus salt blast cycle	EMMA/EMMAQUA	Also. Ref. ASTM F-520, D-756, D-1501, D-1499; and FTMS 406-6024 Simulated "real-world" exposure remains to be correlated versus in-service experience
Coating Embrittlement	AC			N/A
	B	ASTM F-736-81 (falling wt.)	High Rate MTS Beam	Screen baseline vs. uncoated; evaluate after conditioning
Fungus	ABC	MIL-STD-810		
Hail (ice crystal)	ABC	ASTM F-320		
Moisture/Thermal	ABC		Humidity Chamber	

TABLE 3 (concluded)

Transparency Material Configuration:

A. Monolithic Stretched Acrylic
B. Coated Monolithic Polycarbonate
C. Acrylic Faced/Polycarbonate Laminate

Test/Exposure Category	Config.	Test Method Recommendation: Std. Standard or Preferred	Alternate	Evaluation/Comments
Natural Weathering	ABC	45° South [illegible], Fla. or Ariz.) ASTM [illegible] 1435	MIL-P-25690A	Results take too long to generate
[illegible] Temp. Cycle [illegible] Environment	ABC	WPAFB [illegible]		
Rain Erosion	ABC	WPAFB Rotating Arm Test App.	Superimpose water spray on acc. weather	Acrylic performance [illegible] industry standard
Thermal Stability Relaxation	A	MIL-P-25690A		
	B	MIL-P-83310		Doesn't consider mission or life cycle or edge constraint; what are upper temp. bounds?
	C	MIL-P-5425; MIL-P-8184B; MIL-P-25690A		
Thermal Shock	ABC		ASTM F-520-77	Add environmentally conditioned matl. in addition to new baseline matl.
UV/Moisture	ABC	QUV		
Water Absorption	ABC	ASTM D-570		

LIST OF ABBREVIATIONS:

FTM - Federal Test Method
ASTM - American Society for Testing and Materials
AECMA - Association Europeenne des Constructeurs de Materiel Aerospatial
SEM - Scanning Electron Microscopy
QUV - Accelerated Weathering Testor supplied by Q-Panel Co., Cleveland, OH.
HPLC - High Pressure Liquid Chromatography
EMMA(QUA) - Equatorial Mount with Mirrors for Acceleration (plus Water Spray)

It is also noted that recording a stress-strain curve and measuring change in percent elongation (ductility) at high strain rates would be an indicator of degradation resulting from accelerated weathering (embrittlement; impact resistance). Therefore, testing of tensile coupons at high rate and measuring percent elongation is an alternative for consideration to falling weight impact and/or high rate MTS beam tests. Guidelines for specimen configuration can be obtained from ASTM Standard D1822, modified for length and thickness; guidelines for the related testing procedure being obtained from ASTM Standards D638 and D2289.

SECTION 3

EXISTING DEFICIENCIES/CORRECTIVE ACTION

No laboratory test method, combined with simulated environmental conditioning, used to date provides a valid correlation with in-service operational experience. This results from the fact that none of the available test techniques realistically and/or cumulatively simulate (duplicate) the forming, installation, storage, transport, in-flight, flight-line, maintenance, and environmental aging conditions witnessed by today's real world transparencies.

The degradation of the optical properties of transparencies is the single greatest cause for removal and replacement. Pilot complaints of problems and subsequent confirmation by a flight safety officer is the usual path leading to a maintenance action. Five optical qualities for which limits are specified for most transparencies are angular deviation, optical distortion, luminous transmittance, haze, and optical defects. Birefringency limits and color are also specified for some transparencies. No specific tests or criteria are currently in any of the specifications for multiple images or internal reflections. Some optical qualities are inherent in the geometry, manufacturing process, and materials, and remain relatively unchanged after manufacture, while others are subject to gradual change during exposure to the service environment. The desire of the user is to obtain a component of excellent initial quality which is easily maintained and does not degrade with use. Resultant in-service usage problems originate from scratching, haze buildup, delamination, and craze development.

Candidate outer ply plastic materials for aircraft transparency applications remain susceptible to a surface condition known as crazing. These crazes can grow into large fissures, degrade optics, reduce strength, and eventually lead to structural failure. During transparency development, face ply materials must be tested for craze resistance to chemicals anticipated to be present in the operational environment of the aircraft. It is recommended that the currently accepted test method be modified to include consideration of higher stress levels, longer exposure time, and more solvents. Stress, moisture, and temperature all have an influence on the crazing of plastic transparency materials. The contributing effects of each, and combinations thereof, must be defined and simulated during subscale laboratory testing in order to substantiate full scale in-service behavior.

Delamination remains one of the primary failure modes for laminated transparencies and occurs when the adhesive strength of the interlayer-to-substrate bond is exceeded. Although structural degradation is of primary concern, delaminated areas also degrade the optical quality up to the point of requiring transparency replacement. Candidate test methods that are good indicators of interlayer adhesion strength and can be employed during the development cycle to minimize the potential for in-service delamination include flatwise tension, slow rate torsional shear, lap shear, compression shear, and peel. Test specimen configurations and test methods remain to be standardized, although guidelines for similar tests exist within ASTM and/or FTM documents. The correlation between coupon tests and full scale performance remains to be substantiated, as does the effect of laboratory accelerated conditioning compared to "real-world" environmental exposure.

The integration of accelerated flight line environmental exposure with actual flight cycle pressure-temperature simulation at the Building 65 WPAFB Test Facility has demonstrated the practicality of more realistic developmental and qualification testing. The results of the current F-16 laminated canopy tests in that facility have also demonstrated the importance of the test level and the potential pass/fail sensitivity of current transparency materials to these test levels.

Many qualification tests of developmental USAF aircraft transparency designs have been, and continue to be, conducted using new unexposed material. Sufficient data has now been generated to make it evident that environmental conditioning must be experienced by these test specimens prior to test. Such exposure, coupled with a realistic residual stress, and followed by a scanning electron microscopy examination, would greatly advance the state of the art for predicting the durability of transparency configurations.

Data to substantiate QUV as a valid accelerated simulation of combined moisture/UV look promising. Techniques to superimpose representative stress levels on coupons during exposure appear simple and meaningful. Post test evaluation using SEM has shown it to be an invaluable tool, as evidenced by the following excerpt taken from the Reference 8 report.

> "Visual observations of coating damage and coating removal are an effective means of making relative comparisons between materials. However, visual observations are limited in their ability to determine erosion mechanisms in coated transparent materials."

"Scanning electron microscopy techniques are most effective in assessing the role of mechanistic processes in rain erosion phenomena. These techniques can detect incubation and initiation stages, erosion characteristics, i.e., pitting, cratering, and microcracking, and adhesion characteristics of coated materials."

SECTION 4

TEST METHODOLOGY AND EVALUATION CRITERIA DEVELOPMENT

Figure 7 presents, in outline form, a proposed development of test methodology for evaluating the durability of high performance USAF transparency systems that is both realistic and cost effective. Tests required to evaluate the three material configurations under study, i.e., monolithic stretched acrylic, coated monolithic polycarbonate, and acrylic faced/polycarbonate laminate, are delineated. All durability testing would be accomplished during the preproduction phase of transparency development, emphasis being placed on early coupon articles. Real world exposure conditions will be defined along with corresponding laboratory simulation techniques so that all levels of testing will provide a significant improvement in test data correlation with in-service usage. Test/exposure methods will be developed to thoroughly evaluate the failure mechanisms of delamination, coating loss, impact resistance, abrasion, and crazing. Section 2 presents a compilation/analysis of the base of knowledge used to select the test methodology outlined in Figure 7.

Based on this outline, guidelines for conducting all tests for the durability evaluation, with the appropriate specimen conditioning, simulation procedure, and conformance requirements have been compiled and are documented in the Part II report. The rationale used to establish the numerical values stated in the recommended acceptance criteria is based on an assessment of (a) existing military specifications for the appropriate material; (b) the F-16 transparencies critical item development specification; (c) the Reference 3 report; (d) the Section 2 information analysis of this report; and supplemented by (e) the judgement of the authors.

PHASE OF TRANSPARENCY DEVELOPMENT

PRELIMINARY DESIGN

(Mission requirement, baseline layout, general arrangement, tradeoff of desired aero. vs physical limitations)

DETAIL DESIGN (CONFIGURATION DEFINITION) AND PRE-PRODUCTION (PROTOTYPE DEVELOPMENT)

DURABILITY* EVALUATION (UNDER CONTRACT F33615-81-C-3421)

PRODUCTION

(Shop liaison, field maintenance, design derivatives)

Test and Material Configuration	Exposure Magnitude* (or Upper-Lower Bound) and Method of Simulation (Acceleration Factor)		Pass/Fail Criteria: Per Year	Pass/Fail Criteria: Service Life
COUPONS - MONOLITHIC STRETCHED ACRYLIC Chemical Craze Beams After Conditioning Haze and Transmittance after Conditioning Impact - Baseline and Conditioned - Falling Weight or High Rate MTS Beams Abrasion Resistance - Baseline and Conditioned - Inflight and Flightline Thermal Shock	In-Flight	UV, Pressure, Impact, Temp, Thermal Shock, Moisture, Rain-Ice/Hail, Fatigue and Crack Prop.		
COUPONS - COATED MONOLITHIC POLYCARBONATE Chemical Craze Beams after Conditioning Haze and Transmittance After Conditioning Coating Adhesion - Expose to QUV (or EMMAQUA) plus Stress - Rain Erosion with SEM Evaluation Coating Embrittlement - Baseline and Conditioned - Falling Weight or High Rate MTS Beams Abrasion Resistance - Baseline and Conditioned - Flightline and Inflight Thermal Shock	Flight Line	UV, Temp, Moisture, Weathering, Cleaning Abrasion, Chemical Exposure		
COUPONS - ACRYLIC FACED/POLYCARBONATE LAMINATE Chemical Craze Beams after Conditioning Interlaminar Bond Integrity (Delamination) - Flatwise Tension, Torsional Shear, and Wedge Peel - Baseline and after Exposure Haze and Transmittance - Baseline and after Conditioning Impact - Baseline and Conditioned - Falling Weight or High Rate MTS Beams Thermal Shock after Conditioning Abrasion Resistance - Baseline and Conditioned - Inflight and Flightline	Installation	Stress		
	Transport/Storage	Thermal		
SUBSCALE - ALL THREE TRANSPARENCY MATERIAL CONFIGURATIONS Three-Point Edge Attachment Beams - Baseline - Static and High Rate Impact - Air Cannon - Baseline and Conditioned	Fabrication/Forming	Stress		
FULL SCALE - ALL THREE TRANSPARENCY MATERIAL CONFIGURATIONS (GFE) Pressure/Temp Cycle - Conditioned - WPAFB Bldg 65 Birdstrike - Baseline (and Conditioned?) - AEDC	To be Defined Considering			

DOCUMENTATION Compile report containing
a) Summary of tests to be conducted, by phase, with conformance requirements
b) Assembly of test methods to be used
c) Listing of required lab equipment capabilities required for each test procedure

* Identified as condition having greatest impact on durability

Comments (Preliminary Design):

Basic material properties and design allowables are required.

A deficiency in data exists to define the environmental, time-dependent, and strain-rate effects on these properties

Existing material MIL-SPECS need critique/revision.

A new spec is needed to control interlayers.

Procurement spec. to control raw polycarbonate is needed

As new candidate materials become available
- generate substantiating data bank and issue appropriate specs

Consider creep, melt flow index, molecular weight, toughness/K factor (resistance to crack propagation), thermal stability (upper-lower limits) during critique/revision of material specs

Comments (Production):

Provide adequate quality control in shop.

Revise/update technical orders to protect optics.

Inspect for internal strain using polarized light

Figure 7. Outline of Test Methodology Development for Durability Evaluation of High Performance USAF Transparency Systems.

SECTION 5

CONCLUSIONS/RECOMMENDATIONS

The developed test methodology for evaluating the durability of high performance USAF transparency systems, as presented in Part II, represents a realistic and cost-effective approach. In our opinion, it represents a significant improvement over present practice for ensuring better in-service performance of plastic transparencies. It is not intended to be overwhelmingly all-inclusive and therefore prohibitive in cost, or impossible to accomplish during the preproduction phase of transparency development. Rather, it is designed to provide the maximum amount of reliable data, in a timely manner, using a minimum amount of testing.

Some aspects of the resultant methodology remain to be validated, such as simulated in-service exposure correlation and acceptance criteria. Laminated F-16 transparency material is currently being experimentally evaluated for chemical craze, haze/transmittance, and flatwise tension, under AFWAL/FIEA Contract No. F33615-80-C-3401, after being subjected to the following environmental conditions: Australia 45° South Natural; Dayton 45° South Natural; Florida 45° South Natural; DSET (Phoenix) 45° South Natural; Building 65 (W-PAFB) accelerated exposure; EMMAQUA accelerated exposure; QUV accelerated exposure; Sunlighter IV accelerated exposure; and baseline (unexposed). Along these lines, we recognize that a test criteria that is too severe could be as undesirable as one that is not severe enough, since it might unrealistically rule out potentially viable design configurations, and thus drive up development costs, weight, and life cycle cost.

First priority in durability test methodology substantiation should be the delamination, outer ply craze, and thermal shock of acrylic faced/polycarbonate laminates, followed by the other exposure/test parameters specified for this

material configuration. This validation would be accomplished by conducting the tests and exposures defined under Part II, Paragraph 2.3. Next priority would encompass the coating adhesion and embrittlement of polycarbonate. This validation would be accomplished by conducting the tests and exposures defined under Part II, Paragraphs 2.2.3 and 2.2.4. If sufficient data is generated during these investigations, enough common data should be available to provide verification of the remaining exposure/test parameters for all three material systems under study.

REFERENCES

1. Kelley, Malcolm E., An Assessment of Aircraft Transparency System Durability Problems and Knowledge Voids, AFWAL-TM-82-163, Wright-Patterson Air Force Base, Ohio, October 1982.

2. West, Blaine S., Kenneth I. Clayton, and F. Joseph Giessler, Survey of Developmental Testing and In-Service Durability of F-15, F-16, and F-111 Transparencies, AFWAL-TR-81-3151, University of Dayton Research Institute, Dayton, Ohio, January 1982.

3. Clayton, Kenneth I., John F. Milholland, and Gregory J. Stenger, Experimental Evaluation of F-16 Polycarbonate Canopy Material, AFWAL-TR-81-4020, April 1981.

4. Clayton, K. I., P. E. Johnson, B. S. West, and G. J. Stenger, Evaluation of Test Methods for Determining Impact Resistance of Polycarbonate, UDR-TR-82-141, University of Dayton Research Institute, Dayton, Ohio, November 1982.

5. Clayton, K. I., P. E. Johnson, and B. S. West, Evaluation of Impact Resistance Test Methods for Polycarbonate, UDR-TR-80-06, University of Dayton, Dayton, Ohio, January 1980.

6. Stenger, Gregory J., F-16 Laminated Material Characterization, UDR-TR-82-80, University of Dayton, Dayton, Ohio, March 1982.

7. Stenger, Gregory J., Evaluation of a Transparency with Metallic Film Interlayer, UDR-TR-82-39, University of Dayton, Dayton, Ohio, March 1983.

8. Hurley, C. J., J. Zahavi, and G. F. Schmitt, Rain Erosion Evaluation and Analysis of Selected Coated Monolithic Polycarbonate Transparency Materials, AFWAL-TR-82-4029, May 1982.

9. Reinhart, T. J. and E. A. Arvay, Progress in the Development of New Transparent Plastics and Interlayer Materials, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, April 1976.

10. Morgan, R. J. and J. E. O'Neal, The Effect of Thermal History on the Mechanical Properties and Crystallinity of Polycarbonate, McDonnell Douglas Corporation, St. Louis, Mo., April 1976.

11. Olson, J. B., At Last, A Meaningful Windshield Life Test, Sierracin Corp., Sylmar, Calif., April 1976.

12. Wiser, George L., "Transparency Applications of Polycarbonates," Aircraft Engineering, Vol. 43, pp. 18-20.

13. Kolyer, J. M., Stability of Transparent Materials Under Worldwide Climatic Conditions, Rockwell International Corporation, Autonetics Group, Anaheim, CA, April 1976.

APPENDIX A

TEST CATEGORY QUESTIONNAIRE

APPENDIX A

FOR:

MONOLITHIC STRETCHED ACRYLIC

COATED MONOLITHIC POLYCARBONATE

ACRYLIC FACED/POLYCARBONATE LAMINATE

Test Category	Is Test Category Meaningful?		Do you Perform Such a Test?		Per Standard?		If Yes: Which Standard	If No: Alternate Method	General Comments
	Yes	No	Yes	No	Yes	No			
MECHANICAL/PHYSICAL:									
Bearing Strength									
Bond Integrity									
Compression									
Creep									
Fatigue									
Shrinkage									
Flex. Strength									
Formability									
Hardness									
Impact Strength									
Internal Strain									
Load Deformation									
Melt Flow Index									
Molecular Wt.									
Peel Strength									
Shear Strength									
Specific Gravity									
Surface Crazing									
Stiffness									
Tear Resistance									
Tension									
Torsion									
Toughness (Crack Resistance)									
Viscosity									
Workability									

Test Category	Is Test Category Meaningful? Yes	No	Do you Perform Such a Test? Yes	No	Per Standard? Yes	No	If Yes: Which Standard	If No: Alternate Method	General Comments
OPTICAL:									
Angular Deviation									
Birefringence									
Color									
Flaw Detection									
Gloss									
Haze									
Index of Refraction									
Light Diffusion									
Luminous Transmittance									
Scratches									
Spectral Transmittance									
Yellowness Index									
ELECTRICAL:									
Arc Resistance									
Dielectric Constant									
Dielectric Strength									
Volume, Surface Resistance									
ENVIRONMENTAL:									
Abrasion Resistance									
Accelerated Weathering									
Bird Impact									
Deformation Temp.									
Coefficient of Ther. Exp.									
Dimensional Stability									
Chemical Craze									
Flammability									
Fungus									
Hail									

Test Category	Is Test Category Meaningful? Yes	No	Do you Perform Such a Test? Yes	No	Per Standard? Yes	No	If Yes: Which Standard	If No: Alternate Method	General Comments
ENVIRONMENTAL (cont.)									
Natural Weathering									
Rain									
Relaxation (Stress/Thermal)									
Salt									
Specific Heat									
Thermal Conductance									
Thermal Stability									
Thermal Shock									
Warpage									
Water Absorption									
OTHER:									

LMED

8